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Increasing the effectiveness of combined strikers in the defeat of lightly armored targets

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Abstract. The article deals with the possibility of increasing the damaging effects of small-caliber artillery ammunition in the fuel tanks of aircraft and helicopters. A comparison of the results of the calculation of the probability of the incendiary effect of strikers based on fluoropolymers on diesel fuel was made. The calculations were carried out using the methods of “Fragment Criterion” and “Energy Balance”.

1. Introduction

In modern combat, small-caliber barrel artillery is highly effective in fighting both the weakly protected and lightly armored vehicles. These groups of equipment include both ground equipment (infantry fighting vehicles, armored personnel carriers, and their varieties), as well as various types of aircraft. In connection with the recent active use of assault and tactical aviation and helicopters against enemy vehicles, the development and improvement of small-caliber barrel artillery ammunition has become particularly necessary. The effectiveness of the impact on aviation of small-caliber ammunition is the sum of the total number of hits that ultimately led to the disruption of the life support systems and the functioning of the aircraft.

As a result of studies of susceptibility of various types of combat aircraft, 4 main reasons were identified that led to the non-return of aircraft to their bases as a result of opposition from the enemy: a fire or explosion of an aircraft, damage to its power plant, loss of controllability, explosion of ammunition.

From the physical factors affecting important functional units of airplanes and helicopters, an incendiary effect is of great interest.

The main reason for the ignition of fuel in the fuel tanks is that the hull of the aircraft carcass is made of alloys containing aluminum, titanium, and a number of other fairly flammable materials. Upon penetration of the hull, which acts as a kind of screen, a flare of hot dispersed metal is formed.

When a bullet or shrapnel hits a fuel tank, in the space between the hull and the damaged tank wall, the torch of particles and the fuel mixture contact, which causes the fuel to ignite with a certain probability depending on atmospheric pressure, ambient temperature, fuel vapor pressure, mixture concentration and oxygen in the mixture and ambient air. However, the defeat of this type occurs only in the absence of internal complex protection, having a multilayer structure, including foam plastic and latex spongy rubber.



Consequently, the task of creating a new type of small-caliber ammunition, possessing not only the necessary specific energy for breaking through an obstacle, but also the subsequent incendiary over-obstacle effect, which can lead to the destruction of an aviation target, becomes urgent. One of the possible ways to increase the over-obstacle incendiary effect is the use of ammunition and striking elements of reaction materials containing fluoropolymers in their structures.

In the case of studying the interaction of fluoropolymer damaging elements and lightly armored aviation targets, it is reasonable to use a synthetic approach that will allow us to estimate not only the depth and diameter of cavities on the aircraft's flaps and helicopter blades, but also to evaluate the physically complex processes of penetration of fuel tanks with subsequent ignition of the fuel mixture.

2. The main properties of fluoropolymers

It was experimentally proved that fluoropolymers (PTFE) have a lower specific kinetic energy spent on the destruction of an obstacle compared with non-deformed steels and textolite impactors.

Therefore, as the material for the creation of ammunition that can cause incendiary over-the-shoulder action, the fluoroplastic was chosen. PTFE (fluoroplastic F-4, F-4D or Teflon), has a number of unique physicochemical, antifriction and anti-adhesive properties [1-3]. It is inert to aggressive media (up to oxidizing), non-toxic under normal conditions, is a dielectric, heat-resistant and explosion-proof.

PTFE is one of the most stable polymers, but it is thermodynamically unstable. It is known [2-4] that at high temperatures thermo-oxidative destruction of fluoroplastic occurs (which can be prevented by the introduction of special stabilizers) with the formation of hydrogen fluoride, perfluorobutylene, carbon monoxide, fluoroplastic aerosols. Decay to graphite and tetrafluoromethane proceeds with the release of heat (113 kJ).

The main product of the pyrolysis of PTFE in the temperature range up to 600 °C is a heavy gas molecule - tetrafluoroethylene monomer (TFE) containing impurities. According to [3], with the explosion of gaseous TFE, which is at an initial pressure of 10 ... 15 atm., and room temperature, the pressure of decomposition products in a closed volume can increase by 8 ... 10 times. At an initial temperature of 80 °C, TFE becomes explosive when a pressure of 6 atm. is reached (0.6 MPa). It was established experimentally that deflagration combustion of TFE can also go into detonation mode. It is also noted that the probability of explosion (explosive combustion) and the transition of combustion to detonation increases sharply when air is introduced into the TFE.

3. Experiments to determine the destructive ability of fluoropolymers

When conducting laboratory studies of high-speed interaction with aluminum-containing barriers of impactors made of various materials, the effect of the high destructive ability of impactors made of PTFE relative to other polymeric materials and steel impactors was revealed [7, 8]. The experiments were carried out on a ballistic stand, which allows throwing impactors with a caliber of 13, 23, 33 mm, a length of 1 to 12 calibers with speeds of 300 ... 1500 m/s. Sheets and plates made of aluminum alloys were used as barriers: Al-Mn, Al-Mg, duralumin, multilayer bags of these materials; elements of the airframe and helicopter blades, as well as materials: steel, wood, textolite.

When conducting firing tests on an obstacle from Al-Mn with impactors made of polyethylene, ebonite, textolite and fluoroplastic (with a fixed initial kinetic energy of the impactors), in [7] caverns were obtained, which significantly differ in their parameters. The largest parameters of the cavities in diameter, depth and volume corresponded to the fluoroplastic strikers. In addition, experimental studies have shown that at speeds of impact of PTFE strikers of about 600 m/s and higher, a black deposit of carbonized products was formed on the surface of the cavity and around it in a radius of up to 6 ... 8 calibers of a striker. In order to determine their chemical composition, black particles collected from the cavity with a dissecting needle were subjected to x-ray phase analysis, which

showed that the particles under study consist of aluminum metal and aluminum fluoride AlF_3 . The black color of these particles is caused by the presence of soot on them.

X-ray phase analysis of the chemical composition of the products of interaction between a fluoroplastic striker and an Al-Mn obstacle showed that the particles studied were a mixture of metallic aluminum, carbon black and aluminum fluoride AlF_3 . This suggests that with the impact interaction of the fluoroplastic striker with an aluminum-containing obstacle between the firing material and the friction material, an exothermic chemical reaction may occur.

4. Experimental confirmation of the thermochemical reaction hypothesis

To confirm the hypothesis of the thermochemical reaction between the fluoroplastic and other light alloys, experiments on the interaction of fluoroplastic strikers with obstacles of titanium alloys, VT1-0 and VT-20, were conducted. Analysis of the results of the experiments shows that during the impact of strikers containing fluoroplast with obstacles based on titanium alloys, a characteristic black scurf of interaction products is formed on the surface, similar to that formed when interacting with an aluminum-containing obstacle. This allows us once again to assume the occurrence of a chemical reaction between the fluoroplastic and titanium obstacles.

X-ray phase analysis of the chemical composition of the products of the interaction of the fluoroplastic and obstacles from titanium alloy showed that the layers, identified in the region of the cavity and not having a diffusion layer with the base material of the sample, consist of titanium and fluorine. On the layers there were found particles having a spherical shape of different sizes (1-15 microns), which contain iron, titanium, oxygen, fluorine, and as impurities - aluminum, sulfur, chlorine. No fluorine compounds with titanium TiF_2 , TiF_3 , TiF_4 were found. This fact is explained by the fact that titanium fluorides, in contrast to aluminum fluorides [9], are volatile compounds. Conducting experiments in a closed volume made it possible to fix not only the fact of an increase in the cavity and the presence of soot on its surface, but also the presence of titanium fluorides. It is possible to estimate the amount of heat generation in the process of interaction between a striker and an obstacle by the colors of the tread of the face layers in the contact zone - their heating temperature was about 500 °C.

A change in the microstructure of the titanium alloy after dynamic loading was also investigated. The study of the microstructure was performed on an NEOPHOT-21 optical microscope in reflected light at magnifications: x200 and x1000. The microstructure of the studied samples in areas at a distance of about 40 mm from the zone of destruction is shown in Figure 1. It can be seen that it consists of deformed, strongly twinned grains (such a structure is characteristic of hot-rolled plates of the VT1-0 alloy). In the zone located near the zone of destruction, the grains are deformed (see Figure 1b) and have a fibrous appearance. The greatest interest are cracks. Beginning on the surface, the cracks go deep into the metal and break off, without tapering. From the tops of the cracks, narrow bands with a recrystallized fine-grained structure follow (see Figure 1c). A similar structure also surrounds the crack.

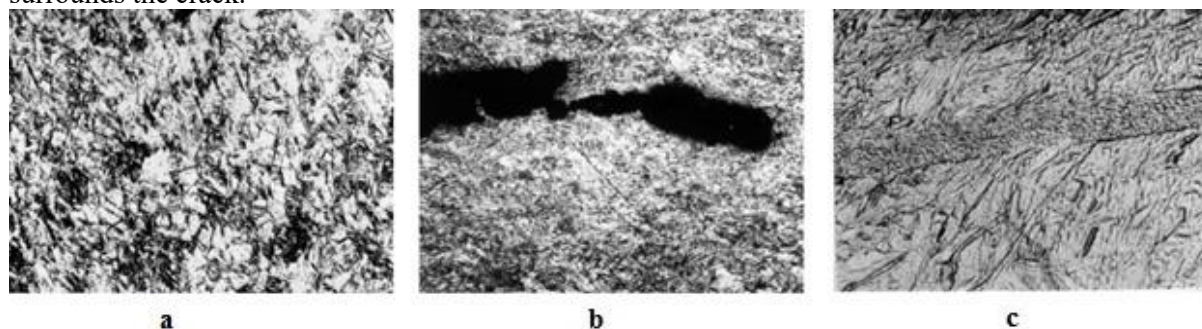


Figure 1. The microstructure of the investigated templates:

a - initial state x200; b - crack x200; c - strip x1000.

5. Use of fluoropolymers as materials for small-caliber artillery ammunition

Studies conducted under various experimental conditions show a high heat release, which has necessitated the testing of assumptions about the high incendiary ability of fluoropolymers based strikers.

When considering the physical meaning of this process, it should be noted that this is possible due to the presence of a thermo-oxidative destructive reaction of fluoropolymers in high-speed interaction with light alloys based on titanium and aluminum [14]. The pressure arising at the interface between the obstacles and the striking element exceeds the minimum pressure required for an exothermic explosion-like reaction, accompanied by the release of aluminum or titanium fluoride [15]. In the process of impact, such striking elements are deformed and destroyed, which, together with the explosion-like reaction, leads to an increase in the holes and multifactorial (thermobaric and high explosive-incendiary) action in the over-obstacle space. When dispersed clouds consisting of fluoroplastic and titanium or aluminum particles reach the back side, it expands instantly, which increases the diameter of the cavity, the edges of which are bent to the outside, forming a star-shaped form in the case of thin layered obstacles. High temperature and the resulting small condensed products disrupt the electronic devices of the instrument compartments of the target.

Considering the penetration process of any firing striker (losing mass in the penetration process or deforming) into the obstacle, it can be noted that the layers of the obstacle's material and the deforming striker move in parallel, and an explosive reaction takes place based on the thermal-oxidative processes between the striker and the material of the obstacle. The processes of parallel oxidation were considered on various types of gas mixtures and formed in the Counterflow Diffusion Flame (CDF) method, first proposed by Tsuji and Yamaoka [16].

The results obtained in the course of experiments [17] confirm the mathematical model of the interaction of fluoroplastic strikers and obstacles based on light alloys, proposed by the authors, which makes it possible to proceed to the consideration of specific practical problems.

6. Experiments to determine the incendiary effects of strikers

The determination of the incendiary effect of fluoroplastic ammunition on the fuel and oil-conducting system was carried out on the installation "Ballistic stand". The scheme of the experiment is shown on Figure 2.

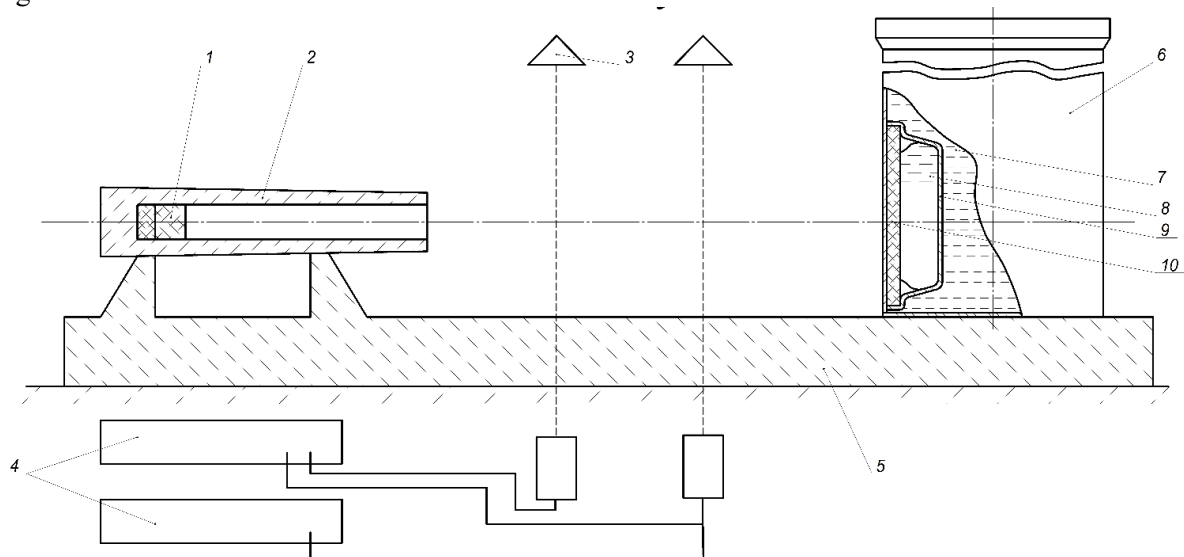


Figure 2. Installation scheme "Ballistic stand": 1 - striker; 2 - artillery installation; 3 - photoblocking; 4 - ballistic chronograph; 5 - base; 6 - tank body; 7 - catcher (water); 8 - fuel; 9 - jumb; 10 - sponge latex rubber.

A steel with a sponge latex rubber interlayer that did not react with fluoropolymers was chosen as the material of the fuel tank body, which will make it possible to estimate the pure incendiary effect that arises directly from the penetrating striker, without the influence of aluminum or aluminum-titanium shell of the air target. Winter diesel fuel (DF) with lower flammability and viscosity characteristics was taken as fuel. To assess the influence of factors (the shape of the head part, possible combinations of PTFE and aluminum) affecting the incendiary effect, experiments were carried out with strikers of various configurations.

The designs of the impactors used for the experiments are presented on Figure 3.

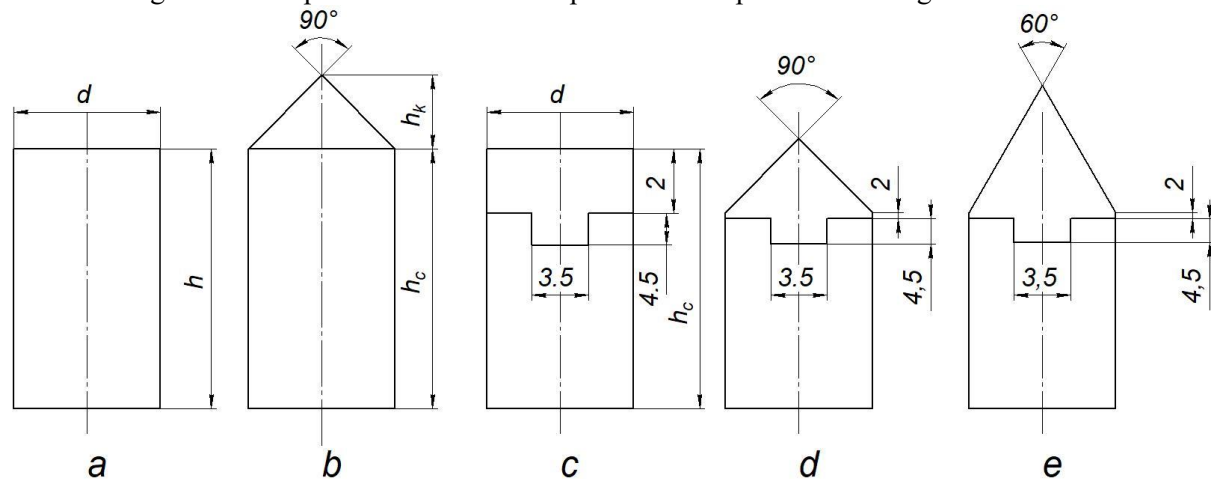


Figure 3. Striker's types: a - striker of a cylindrical shape (fluoroplastic, steel); b - striker with a tapered part and a vertex angle of 90° (fluoroplastic, steel); c - striker from Al and Ft with a vertex angle of 180° ; d - striker from Al and Ft with a vertex angle of 90° ; e - striker from Al and Ft with a vertex angle of 60° .

A series of results of experiments to determine the incendiary of the under-obstacle action are shown in Table I. Analysis of the results of the shooting shows that the ignition of the fuel occurred during the testing of combined strikers from Al-Mn alloy and fluoroplastic and individual strikers from pure fluoroplastic.

Table 1. The results of experiments on the ignition of fuel for the combined obstacle.

Striker's material/vertex angle, α°	Mass, g	Initial contact velocity, V_c , m/s	Result: + ignition – no ignition
Al-Mn alloy + Ft / 180°	9	1006,32	+
Al-Mn alloy + Ft / 60°	9	1153,91	+
Ft / 180°	9	916,34	–
Ft / 180°	9	989,17	–
Ft / 180°	9	1013,18	–
Ft / 90°	9	898,11	–
Ft / 90°	9	916,58	–
Ft / 90°	9	918,51	–
Ft / 90°	9	1128,53	+
Ft + Al-Mn alloy / 180°	9	863,12	–
Ft + Al-Mn alloy / 180°	9	1106,64	+
Ft + Al-Mn alloy / 90°	9	986,15	+
Ft + Al-Mn alloy / 90°	9	1092,88	+
Steel / 180°	9	1025,69	–
Steel / 90°	9	864,54	–

7. Evaluation of incendiary actions by the method of "Fragmentary criterion"

One of the most common ways to assess the incendiary effect of fragments, damaging elements and bullets is the method of evaluation by the "Fragmentary Criterion" [18].

When assessing the probability of fuel ignition in this method, the impact impulse of a fragment is calculated:

$$i = 0.000204 \cdot m^{1/3} \cdot v \quad (1)$$

where m is the mass of the fragment, g;

v is the velocity of the fragment, m/s.

With a specific impulse $i \leq 0.16$, the probability of ignition is zero. With a specific impulse $i \geq 2.5$, the probability of fuel ignition is close to unity. Analyzing the source data for the specific impulse laid down in the "Fragmentary criterion" method, an approximation dependence to determine the probability of fuel ignition was obtained:

$$p = 1 + 1.08 \cdot e^{-4.16i} - 1.96 \cdot e^{-1.46i} \quad (2)$$

The dependence of the probability of fuel ignition on the kinetic energy (E_k) is shown on Figure 4. However, when using the fragmentation criterion, all dependencies were built on the basis of the calculated specific impulse, which depends on the mass of the fragments and the initial interaction velocity, without taking into account the additional energy released during the chemical reaction, between the fluoroplastic and aluminum, which in turn significantly affects ignition of diesel fuel.

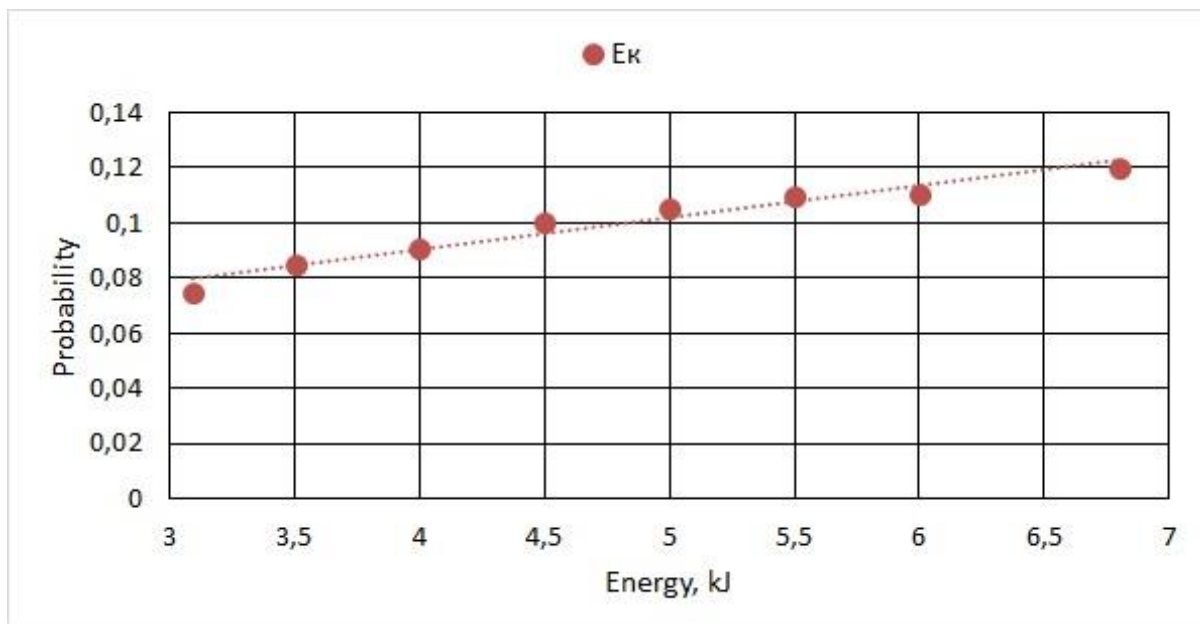


Figure 4. The dependence of the ignition probability from energy.

8. Evaluation of incendiary actions by the method of "Energy balance"

To assess the effect of a chemical reaction on the ignition of diesel fuel in the fuel tanks, an analysis allowing to estimate the amount of energy released in the process of a chemical reaction spent on heating diesel fuel to a self-ignition temperature was carried out.

As a result, two types of simplified models were obtained: assembly No. 1 and assembly No. 2 (see Figure 5a and Figure 5b). The total mass of the striker was 9 grams, in accordance with the conditions of the experiment. To evaluate possible reactions, the mass of fluoroplastic and aluminum in the assemblies ranged from 1 to 8 grams.

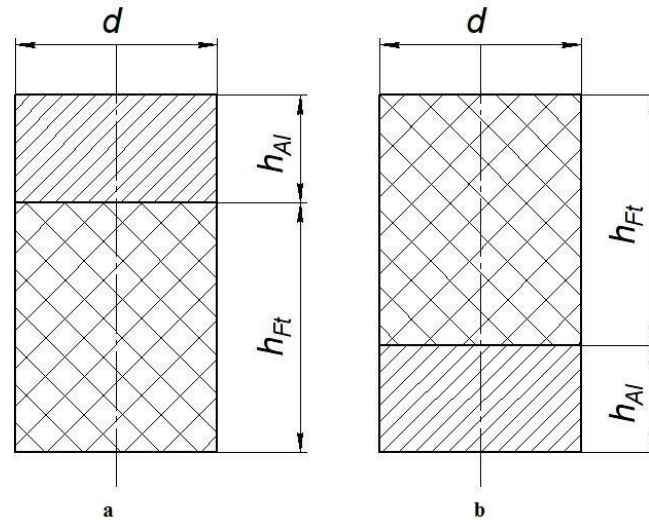


Figure 5. Striker structures for mathematical calculations.

The energy expended on heating diesel fuel while the striker is moving inside the fuel tank will consist of 3 components:

$$E_{st} = E_{react} + E_{def} + E_{dec} \quad (3)$$

where E_{react} – energy released by a chemical reaction, kJ;
 E_{def} – energy released as a result of deformation of a striker, kJ;
 E_{dec} – energy released as a result of deceleration the striker in the fuel, kJ.

The deformation energy of the impactor is determined depending on the relative deformation of the head part of the impactor ε and the dynamic yield strength of the material σ_{df}^* :

$$E_{def} = 0.95 \cdot \frac{S_{mid} \cdot \sigma_{df}^* \cdot \varepsilon}{T^*} \quad (4)$$

where S_{mid} – area of midsection, m²;
 T^* – coefficient of conversion of mechanical energy into heat, kJ;

The analysis performed for various configurations of the striker assemblies shows that the effect of deformation energy on the total energy of the striker is less than 1%, and is not taken into account in further calculations. Probably, such a low value is associated with a short time of the process of movement of the striker in the fuel (about 10–15 μ s), which is clearly not enough for the process of heat transfer from the striker to the fuel.

The deceleration energy of the striker can be calculated from the equations of motion of the striker in the fluid. At the moment of penetration of the striker into inside of the fuel tank, a certain velocity field will appear in the entire volume of the fluid, and the initial velocity of the striker v_{fmax} will be less than the impact velocity of the striker with the liquid v_c . The value of v_c is determined by the method of N.E. Zhukovsky. The conservation law for the moment of impact can be written as:

$$(m + m_0) \frac{dv_f}{dt} = mg - \rho_{DF} gV - c_x \frac{\rho_{DF} v_f}{2} S_{mid} \quad (5)$$

where m_0 – the added mass, kg;
 v_f – striker velocity into inside of fuel tank at every moment in time, m/s;
 c_x – impactor drag coefficient, kgm/s²;
 ρ_{DF} – density of diesel fuel, kg/m³;
 V – drum volume, m³;
 g – coefficient of gravity, m/s².

The initial v_{fmax} and the limiting v_{lim} velocity of a striker in a fluid is defined as:

$$v_{fmax} = v_c \left(1 + \frac{m_0}{m} \right)^{-1}, v_{lim} = \sqrt{\frac{2(mg - \rho g V)}{c_x \cdot \rho \cdot S_{mid}}} \quad (6)$$

The initial impact velocity of the striker with the fluid is determined on the basis of the balance of the kinetic energy of the striker:

$$v_c = \sqrt{2E_{res}/m} \quad (7)$$

where E_{res} – residual energy of the striker, calculated as the difference between the initial energy of the striker and the energy expended on the destruction of the target at the specific energy of destruction of the target equal to $E_{sp} = 766.67 \text{ J/cm}^2$ [18].

The value of the added mass can be determined by the coefficient of the added mass, which is a function of the elongation of the impactor and its volume:

$$m_0 = \mu_0 \cdot \rho_{DF} \cdot V \quad (8)$$

where μ_0 – the coefficient of the added mass.

The coefficient of the added mass was determined by the method of approximation of tabular data for a fluid with a density of 800 ... 1000 kg/m³ [19]:

$$\mu_0 = 0.5187 \cdot \lambda^{-1.342} \quad (9)$$

where λ – the striker relative elongation.

Graphs of the distribution of the added mass for assemblies No. 1 and No. 2, depending on the mass of the fluoroplastic, are presented in Figure 6.

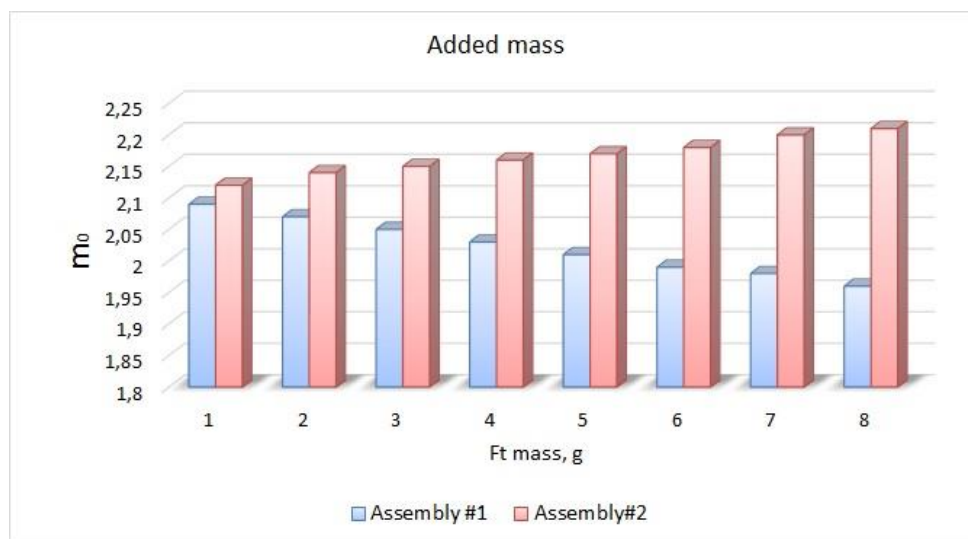
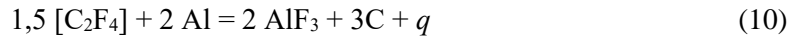


Figure 6. The distribution of the added mass of diesel fuel.

The evaluation of the heat q of the fluoroplastic reaction with aluminum was carried out by thermochemistry [4 – 7]:

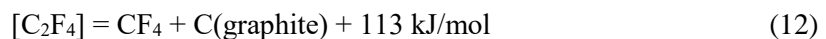


from where

$$q = 1,5 \Delta H_f([\text{C}_2\text{F}_4]) + 2 \Delta H_f(\text{Al}) - 2 \Delta H_f(\text{AlF}_3) - 3 \Delta H_f(\text{C}) \quad (11)$$

where ΔH_f is the molar enthalpy ($\Delta H_f(\text{Al}) = \Delta H_f(\text{C}) = 0$; $\Delta H_f(\text{AlF}_3) = -1490$ kJ/mol; $\Delta H_f([\text{C}_2\text{F}_4])$ is the unknown quantity).

So, use the well-known reaction:



From here:

$$\Delta H_f([\text{C}_2\text{F}_4]) = 113 + \Delta H_f(\text{C}) + \Delta H_f(\text{CF}_4) \quad (13)$$

Since $\Delta H_f(\text{C}) = 0$, $\Delta H_f(\text{CF}_4) = -907$ kJ/mol, then $\Delta H_f([\text{C}_2\text{F}_4]) = 113 - 907 = -794$ kJ/mol.

Then, the heat of reaction of fluoroplastic with aluminum will be equal to:

$$q = 1,5 (-794) + 2 \times 1490 = 1789 \text{ [kJ/2 mol AlF}_3 \text{]} \quad (14)$$

Thus, when the fluoroplastic interacts with aluminum, heat $q = 895$ kJ/mol is released.

The molar mass of aluminum in the reaction $M(\text{Al}) = M_r(\text{Al}) \cdot 2 = 53.96$ g/mol, the molar mass of the fluoroplastic in the reaction $M(\text{Ft}) = M_r(\text{Ft}) \cdot 1.5 = 798.525$ g/mol, where $M_r(\text{Al})$ and $M_r(\text{Ft})$ is the molecular weight of aluminum and fluoroplastic, respectively.

Then, it is necessary to find the number of moles of a substance that, after being introduced into the wall of the fuel tank, enter into a chemical reaction. The number of moles of aluminum and moles of fluoroplastic capable of reacting is defined as the ratio of the mass of aluminum and fluoroplastic to the molar masses of aluminum and fluoroplastic:

$$N_{\text{Al}} = \frac{m_{\text{Al}}}{M(\text{Al})}; N_{\text{Ft}} = \frac{m_{\text{Ft}}}{M(\text{Ft})} \quad (15)$$

To determine the heat released during the passage of a chemical reaction, select the smallest number of moles of substances (fluoroplastic or aluminum) that can react and multiply this value by the amount of reaction heat calculated by thermochemistry methods:

$$E_{\text{react}} = N_{\min(\text{Al}/\text{Ft})} \cdot q \quad (16)$$

The amount of caloric spent on heating the fuel to the self-ignition temperature is:

$$Q = C \cdot m \cdot (t_2 - t_1) \quad (17)$$

where t_1 – initial temperature (20 °C);
 t_2 – self-ignition temperature of DF;
 C – average specific heat for temperature range;
 m – mass of the DF (1 g).

To determine the effectiveness of the incendiary effect of assemblies No. 1 and No. 2, we define the mass of diesel fuel brought to ignition as:

$$m_{iDF} = E_{st} / Q \quad (18)$$

The results of the calculations are presented in Figures 7 and 8.

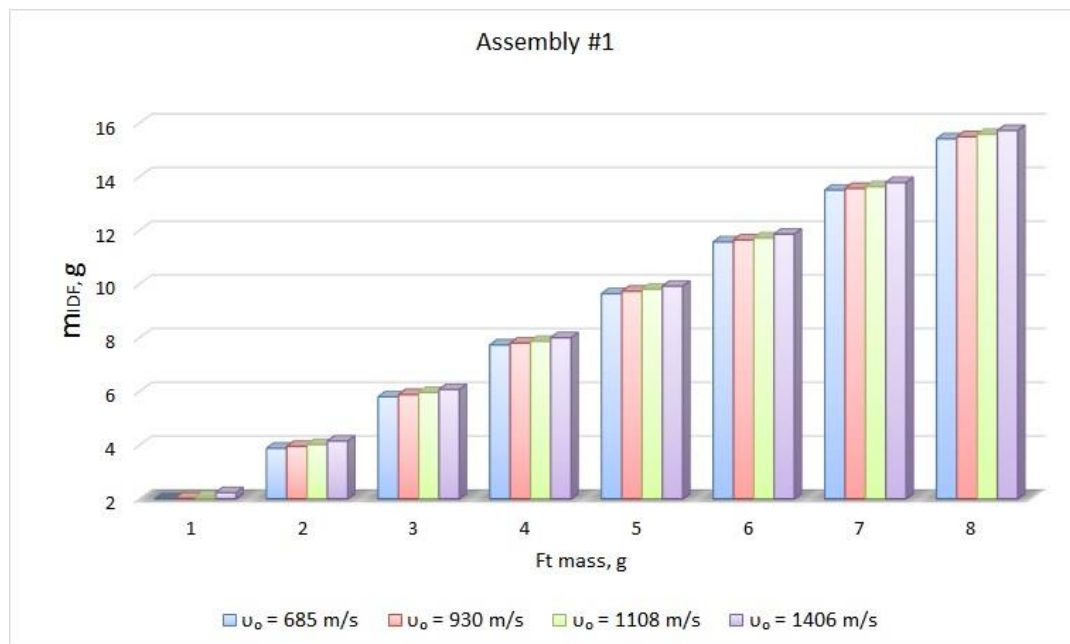


Figure 7. The mass of ignited DF depending on the mass of Ft in assembly No. 1.

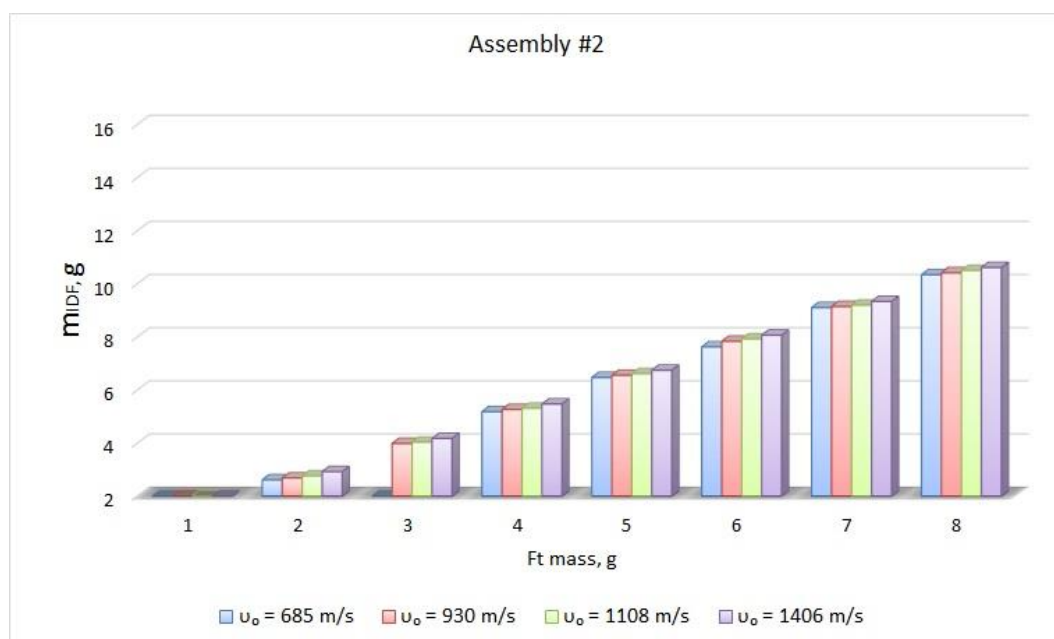


Figure 8. The mass of ignited DF depending on the mass of Ft in assembly No. 2.

The obtained results of calculations on the possible weight of ignited diesel fuel are in good agreement with the results of experiments that show steady ignition and combustion of fuel under the influence of the presented assemblies of strikers.

9. Conclusions

Studies have shown that fluoropolymers can, under dynamic loading, release enough energy to heat a certain amount of fuel to ignition temperature, which with a high degree of probability will lead to the ignition of all fuel in the tank. Thus, creating combined striker elements, including fluoroplastic,

aluminum or titanium, along with an impact-penetrating effect sufficient to defeat thin-walled targets, will have a high inflammatory prohibitive effect.

Conducted studies on the ignition of one of the most resistant to ignition fuels - diesel fuel, gives the right to assume that light with high octane fuel used in aviation will ignite at lower interaction speeds. But at the same time, the speed of interaction should still be higher than the critical speed of the beginning of a chemical reaction between the fluoroplastic and aluminum or titanium.

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